NASA ASTROBIOLOGY INSTITUTE ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Project Report: From Molecular Clouds to Habitable Planetary Systems

Project Investigators:	Alan Boss , R. Paul Butler , Sara Seager , Sean Solomon , Alycia Weinberger , John Chambers

Project Progress

1. *Protoplanetary and Debris Disks*

   Co–I Weinberger pursued studies of young stars to assess the number with circumstellar disks as a function of age and to measure detailed properties of extant disks. Using the Keck Observatory, she searched for disks around stars of age 10 to 100 Million years (Myr) using sensitive 12– and 18–μm photometry. Each association of stars, composed of a few tens of stars that were formed from the same parent molecular cloud at the same time, provides a laboratory for the study of disk evolution. Work on the first of these associations, TW Hydrae, showed that terrestrial planet formation must never have happened or be nearly complete in these 8–Myr–old stars (Figure 1). Results from a second association, 12–Myr–old Beta Pictoris, showed that a larger fraction of stars had disks. Together, the two associations show that the progress of dust removal and planet formation is not a straightforward function of age.

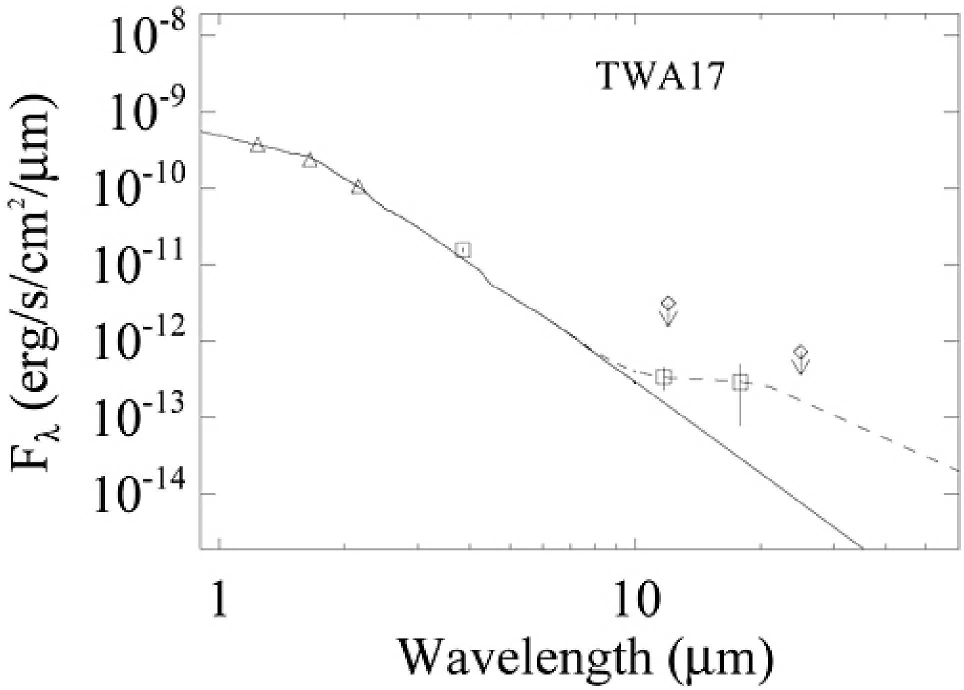

Figure 1. Discovery of a new but very tenuous disk around the 8−Myr−old star TWA 17. This spectral energy distribution shows excess radiation at 12 and 18 microns (open squares) above that expected from the stellar photosphere (solid line). Infrared excess is the signature of disk dust that absorbs stellar light, heats up, and reradiates it at longer wavelengths. TWA 17 was the only star in a survey of sixteen that had detectable dust. The rapid disappearance of large amounts of dust around these sample stars may mean that any planet formation in the terrestrial planet region was completed very quickly. The photosphere was fit to 1−2 micron data from the 2MASS catalog (triangles). The completeness level of the IRAS survey at 12 microns and extrapolated to 18 microns (diamonds) demonstrates that this disk is too tenuous to have been detected by IRAS. The infrared measurements are from the W. M. Keck Observatory. The dotted line shows a 170−K blackbody, the best fit (i.e., color temperature) to the excess measured, corresponding to an integrated dust luminosity relative to the star of L(IR)/L(*)=0.005. (From Weinberger et al., 2004).

Postdoctoral Fellow Aki Roberge and Weinberger have worked extensively to use the Hubble Space Telescope for "coronagraphic spectroscopy," i.e., spatially resolved optical spectra of circumstellar disks. They applied their reduction technique to spectra of TW Hydra and showed that the star’s dust disk scatters blue light in the inner part of the disk but neutrally in the outer part of the disk. This is most easily understood if the size of the dust particles is smaller in the inner than the outer disk. They have successfully applied for Hubble Space Telescope time to study HR 4796A’s disk with the same technique.

Roberge is also using far−ultraviolet (UV) spectroscopy to study three young stars surrounded by circumstellar dust disks using the orbiting

Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. The observations sensitively probe for small amounts of circumstellar gas in the disks, in an effort to set a limit on the timescale for gas giant planet formation and also to investigate the composition of the planetary bodies producing the observed dust disk. One of three targets was observed this year; the other two remain to be scheduled.

The only way one can currently examine the chemistry of extrasolar cometary systems is to look for such systems around carbon−rich AGB stars, where they will be vaporized by their aging star. In carbon−rich environments, one expects no oxygen−containing molecules other than CO and small amounts of SiO and HCO^+. Postdoctoral Fellow Saavik Ford attributes any other oxygen−containing molecules found in carbon−rich environments to a vaporizing cometary system, analogous to the Solar System's Kuiper Belt. So far, one extrasolar cometary system has been discovered around a carbon−rich AGB star, specifically IRC+10216, through the detection of water vapor by Ford and her colleagues. Ford has searched for two other interesting oxygen−containing molecules around IRC+10216, formaldehyde (H_2CO) and methanol (CH_3OH). Both may have played a role in pre−biotic chemistry on the early Earth. She has successfully detected formaldehyde around IRC+10216, at abundances comparable to those found in Solar System comets; however, her observations failed to detect methanol and set a stringent upper limit on the abundance of methanol which is more than an order of magnitude lower than the typical methanol abundances found in Solar System comets.

Ford has looked at possible observations of other extrasolar cometary systems using the Atacama Large Millimeter Array (ALMA), which will exceed the sensitivity of current instruments by factors of 20−100. ALMA should be capable of conducting a chemical survey of a large (~10−15) number of extrasolar cometary systems. Ford is planning to search for HDCO (singly deuterated formaldehyde) around IRC+10216, as detection would be exciting evidence supporting the existence of comets around that object. Ford is also planning to map the formaldehyde emission around IRC+10216, since she has preliminary evidence of a non−spherically symmetric distribution of cometary bodies. Ford, along with Postdoctoral Fellow Nader Haghighipour, is also supervising an undergraduate student who is running dynamical models to examine the possibility that the non−uniform distribution of cometary bodies around IRC+10216 is caused by the gravitational influence of a planet.

2. *Formation of Habitable Planetary Systems*

Co−I Boss is widely recognized as the leading advocate of the disk instability mechanism for the rapid formation of gas and ice giant planets. The rapid formation of self−gravitating clumps of gas and dust in a marginally gravitationally unstable disk requires a reasonably efficient means of cooling the disk gas. Clumps form on the dynamical time scale of a few orbital periods in the disk instability scenario.

Radiative transfer is not able to cool the midplanes of optically thick protoplanetary disks fast enough to permit the disk instability mechanism to form dense clumps. However, vertically−oriented convective cells, driven by the temperature gradient between the disk's midplane and surface, appear to be capable of cooling the disk midplanes on the desired timescale. Boss demonstrated this possibility by analyzing in detail the vertical convective energy fluxes in the first three−dimensional (3−D) radiative hydrodynamics model of clump formation by disk instability. Transient convective cells can be seen in all simulations to date, with vertical velocities (about 0.1 km/sec) and energy fluxes large enough to cool the outer disk at the desired rate (Figure 2). These models strongly support the idea that giant planets may form rapidly by the disk instability mechanism. Boss has also shown that gravitational torques and convective flows are able to transport material across the solar nebula, possibly accounting for the outward transport of thermally annealed grains that are observed in comets.

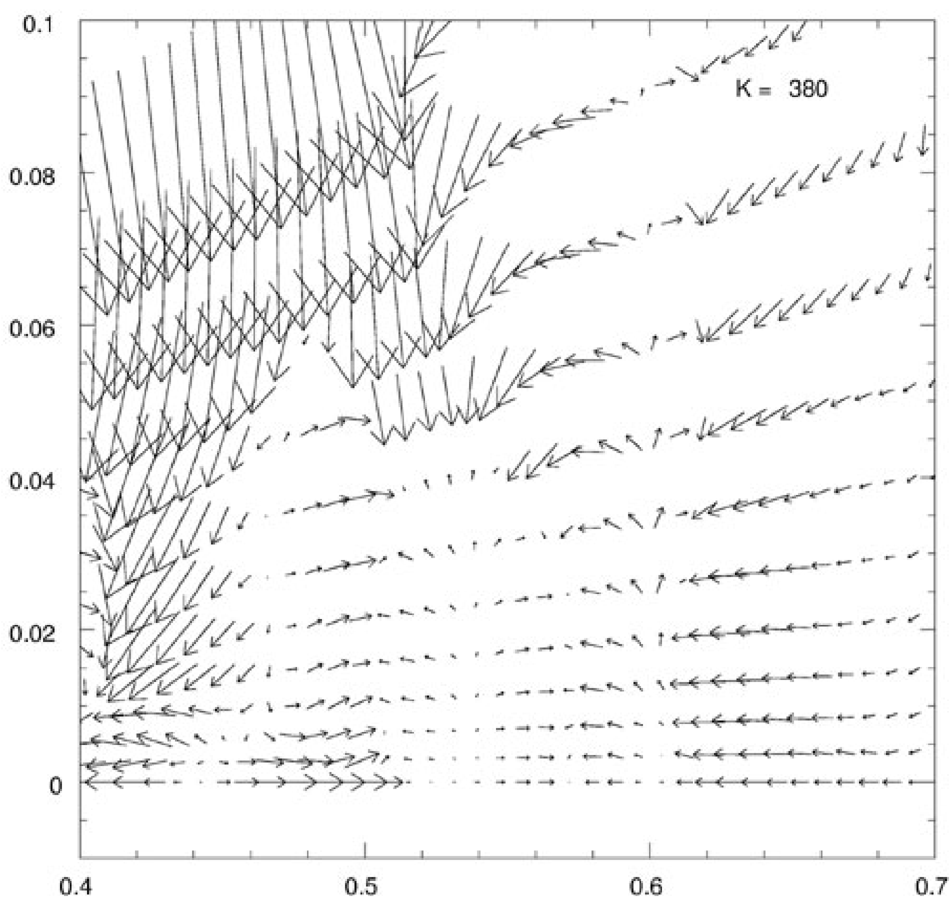

Figure 2. Convective cells can be seen in this vertical cross−section of a planet−forming disk modeled in three spatial dimensions. These cells carry thermal energy away from the disk's midplane to the disk's surface, allowing the disk to remain cool while forming self−gravitating gaseous protoplanets by the disk instability mechanism. A vertical plane at azimuthal grid cell number K = 380 (out of a total of 512 azimuthal

grid points) is shown. The region shown extends from a distance of 8 AU to 14 AU from the central solar−mass protostar. The vertical axis has been expanded by a factor of three to make the convective motions more apparent. The top of the plot is located at 2 AU above the disk midplane, which lies close to the bottom edge of the plot. Symmetry through the midplane is assumed in the calculation, so that the vertical velocities are forced to vanish at the midplane. The maximum velocity vector plotted has a speed of about 2 km/s (From Boss, 2004).

Haghighipour continued his research on the formation of cm−sized objects in the vicinity of off−axis pressure−maxima in a marginally gravitationally unstable disk, and he also studied the dynamical evolution and long−term stability of habitable planets in multi−gas giant extrasolar planetary systems. Results on the first subject indicate that small dust grains, while sweeping up the sub−micron particles of the background, undergo gas−drag−induced migration toward the location of pressure maxima, where they quickly accumulate and create a turbulent layer of cm−sized objects. The study included the effect of the evolution of the disk through changes of the disk's physical parameters on the rate of the formation of the dust grain layer, and also the collision and coalescence of dust grains in such an environment.

Haghighipour also studied the long−term stability of the Gamma Cephei system, where a Jupiter−like planet revolves around the primary star of a binary star system, the dynamical stability of a planetary system embedded in the Beta Pictoris debris disk, and the dynamical evolution and stability of the extrasolar planetary systems Upsilon Andromedae, 47 Ursa Majoris, 55 Cancri, and GJ 876. The latter work was performed in collaboration with Postdoctoral Fellow Eugenio Rivera and with Ferenc Varadi and William Moore of the University of California, Los Angeles (UCLA) NAI team.

Rivera performed dynamical fits to the radial velocity data of stars hosting at least two extrasolar planets. Planet−planet perturbations were included in modeling the data. Ideally, this fitting algorithm could be used to constrain the planets' masses and their orbital inclinations. The method has been used primarily to fit the radial velocity data for the star GJ 876. So far, the GJ 876 planetary system is the only one for which the inclusion of the planet−planet perturbations produces a very significant improvement in the fits to the radial velocity data. This is due to the strong perturbations between the planets, which are in a 2:1 mean motion resonance. Additionally, the code has been used to generate the initial conditions used in long−term stability studies of several extrasolar planetary systems. These initial conditions have also been used to identify regions in multi−planet extrasolar planetary systems that could harbor terrestrial planets.

Co−I Chambers is developing a new numerical model for the delivery of water and organic material to the early Earth. Current thinking is that the Earth initially formed under conditions that were too hot for such materials to condense, so that the planet probably received most of its current inventory from external sources such as asteroids and comets. The new model updates an earlier model for planet formation developed by Co−I Wetherill and makes it possible to study the delivery of water and organics to Earth−like planets in extrasolar systems. Early results suggest that the water content of extrasolar Earth analogues depends sensitively on the orbits and masses of gas giant planets in these systems.

3. *Searching for Extrasolar Habitable Planetary Systems*

Co−I Butler and his group invented the iodine−cell precision radial velocity technique used by most of the world's planet hunting teams, discovered two−thirds of the known extrasolar planets, and achieved the world's best measurement precision. Over the past year the "California & Carnegie Planet Search" program has found 20 planets with the 10−m Keck, 3.9−m Anglo−Australian, and 3−m Shane telescopes in Hawaii, Australia, and California respectively. Among these discoveries is an approximate Solar System analogue (Figure 3), four new multiple planet systems, and two new sub−Saturn mass planets.

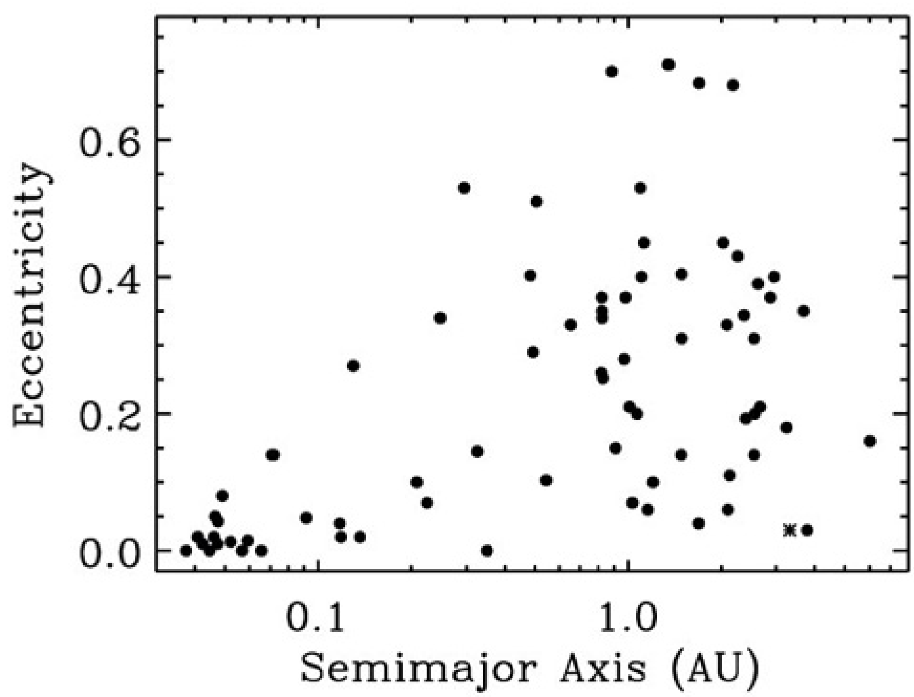

Figure 3. A plot of semimajor axis versus orbital eccentricity for known extrasolar planets highlights the best solar system analog discovered to date from radial velocity measurements. The planet around HD 70642 is in a circular orbit with a 5.8−year period. This discovery is from the Anglo−Australian (AAT) planet search.

Butler’s major remaining goals are the detection of true Solar System analogs (Jupiter− and Saturn−mass planets orbiting beyond 5 AU in circular orbits), and sub−Neptune−mass planets in short−period orbits. In both cases achieving higher spectroscopic precision is critical. Butler and his group are currently surveying all Sun−like stars out to 50 parsecs (pc), a total of about 2,000 stars.

Postdoctoral Fellow Kaspar von Braun continued to pursue the EXPLORE/OC planet transit search program. In the past year, he and his colleagues observed three new open star clusters, bringing the total observed to five. Setting up the EXPLORE/OC survey involved selecting target open clusters using known astrophysical data (available for only a fraction of the Milky Way open clusters) and testing data taken in 2002−2004. Specifically, target clusters have to be centered at the zenith in the middle of the night during a given observing run, and they need to be located nearby (within about 1 kpc) in order to achieve a high signal−to−noise ratio for small stellar radii, which increases the chances for detection of a transiting planet. von Braun and a colleague analyzed the photometric data of the open clusters NGC 2660 and NGC 6208 and conducted the preliminary reduction of test data of about seven target open clusters for future observing runs. Although von Braun's work has not yielded a detection of an extrasolar planetary transit, it has shown the ability to do so, given the observing cadence and relative photometric precision.

In addition to this effort, von Braun has been involved in the analysis of EXPLORE and OGLE data to test different transit−finding and light−curve−phasing algorithms. This analysis includes modeling light curves (together with Co−I Seager) to obtain the period, depth of transit signal, total transit duration, and duration of the flat part of transit (i.e., inside of ingress and egress). Combined with Kepler's third law and the assumption of a stellar mass−radius relation, these observable quantities yield a unique solution of the physical system parameters: stellar mass, stellar radius, planetary radius, orbital radius, and system inclination angle.

4. *Characterizing Extrasolar Habitable Planetary Systems*

In order to understand extrasolar terrestrial−type habitable planets, we must first understand the simpler giant planets. Co−I Seager, together with NAI JPL colleagues Y. L. Yung and C. D. Parkinson, and Caltech graduate student M. C. Liang, studied photochemistry on the hot Jupiters, addressing a major question that relates to observational signatures of hot Jupiters. Jupiter and Saturn have low albedos and muted spectral features blueward of 600 nm due to photochemical hazes. The hazes are produced from CH_4 photodissociation from solar UV radiation and recombination to higher hydrocarbon hazes. One might naively expect that the hot Jupiters, 100 times closer to their star than Jupiter is to our sun, would have vigorous photochemical haze production due to the 10^4 times higher UV flux. Seager and her colleagues found the opposite, namely that hydrocarbons are negligible on hot Jupiters, resulting from the high temperatures—10 times Jupiter's temperature. Despite the high UV flux, the high temperatures allow faster recombination to CH_4 at the expense of hydrocarbon production. In addition, the high temperatures cause a lower CH_4 reservoir to begin with CO as the dominant carbon−bearing molecule at high temperatures. In addition to the photochemical haze result, Seager found that H_2O becomes photodissociated at high altitudes resulting in a huge atomic H reservoir (without UV radiation, all H would be in H_2 at the local temperature). This H reservoir is related to the escape of hydrogen detected by Vidal−Madjar and colleagues. Since hot Earths will probably be detected someday, Seager's work will form the basis for further photochemical studies of extrasolar planet atmospheres.

Seager has continued to interpret extrasolar planet data and make model predictions used by ground− and space−based proposals. Seager and collaborator James Cho have developed a general circulation model for Earth to address Earth's observational signature under different conditions. If Earth had a different rotation rate, obliquity, or continental arrangement, what would the cloud cover fraction and pattern be, and how would this affect either the planet's brightness or its spectral signature? The code is developed, and these questions will be addressed in the coming year.

5. *Habitable Environments in the Solar System*

One of the long−term goals of the CIW NAI team is to assess the likelihood, timing, and physical and chemical characteristics of potential habitable environments on Solar System objects other than Earth. PI Solomon's efforts on this project during the past year have focused on hydrothermal systems on Mars as such candidate environments, primarily because of the influx of important new data from the Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, and Mars Exploration Rover missions. A first step in that evaluation was a synthesis of what can be inferred about the role of water in the early geophysical, geochemical, and geochemical evolution of the planet.

For its first billion years, the planet Mars was at its most active stage, and water linked interior and surface processes. Global differentiation segregated core, mantle, and crust within about 50 Myr of solar system formation; a magnetic dynamo in a convecting fluid core magnetized large areas of the ancient crust; and the Tharsis province became a focus for volcanism, deformation, and outgassing of water and carbon dioxide, possibly in quantities sufficient to induce episodes of global climate warming. A substantial early water budget contributed to widespread erosion, sediment transport, and chemical alteration of crustal material. A more massive early atmosphere was shielded against solar wind stripping by the global magnetic field. Deep hydrothermal circulation of water in the Martian crust likely accelerated crustal cooling and the preservation of variations in crustal thickness. Such circulation chemically altered the carriers of crustal magnetization, likely rendering any residual crustal magnetization beneath the lowest areas of major drainage basins undetectable from orbit, an inference that permits a Martian dynamo to have persisted for as long as one billion years. Such deep penetration of water would also have provided a large volume of crust within which oxidation–reduction reactions at water–mineral interfaces may have yielded energetically favorable environments for organic synthesis and potentially for microbial habitability. Cessation of the dynamo, widespread reduction in the crustal field, and waning of interior outgassing allowed the early atmosphere to dissipate and the planet's surface to cool; substantial quantities of subsurface liquid water may persist to the present.

Highlights

- Weinberger's observations of circumstellar disks in the TW Hydrae and Beta Pictoris associations show that evidence for inner disk clearing is not a simple function of the age of the association.
- Boss's analysis of convective energy fluxes in circumstellar disks strongly supports the idea that giant planets may form rapidly by the disk instability mechanism.
- Chambers's work on the delivery of water–bearing planetesimals to the growing terrestrial planets shows that the efficiency of this process depends sensitively on the presence of the giant planets.
- Butler's spectroscopic survey of all 2,000 Sun–like stars within 50 parsecs yielded a number of new extrasolar planet candidates, including a planet with a minimum mass twice that of Jupiter, orbiting its Sun–like star (HD 70642) on a nearly circular orbit at a distance of 3.3 AU. This system is perhaps the closest analog to our Solar System discovered to date.
- Seager's work on the atmospheres of hot Jupiters has laid the groundwork for understanding the results of future observations of hot Earths.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Kepler	Science Team Member
1	FUSE	Data Analysis
1	MOST	Science Team Member

2	TPF	Planning Support
3	SIM	Planning Support
2	Mars Global Surveyor	Co−Investigator
1	MESSENGER	Principal Investigator
1	Hubble Space Telescope	Data Analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Co−I Boss is on the Science Team for NASA's Kepler mission, which is planned for launch in 2007. Kepler's photometric observations will permit the detection of numerous Earth−like planets in Earth−like orbits around stars in the disk of our Galaxy.

Boss is a member of the Navigator Program Independent Review Team (IRT), reporting to NASA Headquarters, which has oversight responsibility for all elements of the Navigator Program, including the Keck Interferometer, Large Binocular Telescope Interferometer, Space Interferometry Mission, and Terrestrial Planet Finder. Boss chaired a sub−group of the IRT that assessed the TPF Science Roadmap. This assessment led in part to a redefinition of the entire TPF mission concept in 2004.

Co−I Butler is involved with the Space Interferometry Mission, launch date ~ 2009.

Co−I Seager was involved as a Support Scientist on the Microvariability and Oscillations of Stars (MOST) microsatellite (Canadian Space Agency, launched June 2003). Seager was also involved in the NASA Origins Probe study proposals Fourier Kelvin Stellar Interferometer (FKSI) to characterize known planets at IR wavelengths (PI Bill Danchi, NASA Goddard) and Origins Billion Star Survey (PI Ken Johnston, U.S. Naval Observatory).

A member of the NASA Terrestrial Planet Finder Scientific Working Group, Seager contributed as part of a three−person subteam that led the preparation of the science requirements document for TPF.

PI Solomon is a Co–Investigator on the Mars Orbiting Laser Altimeter experiment on Mars Global Surveyor. He is also the Principal Investigator for the MESSENGER mission to orbit Mercury.

Co–I Weinberger was principal investigator on a cycle 9 Guest Observer program for the Hubble Space Telescope entitled "Imaging and Spectroscopy of Dusty Circumstellar Disks."

Field Expeditions

Field Trip Name:

Start Date: June 2003	***End Date:*** July 2004
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Monthly trips to Chile (Magellan Baade Telescope, Las Campanos Observatory), Hawaii (W. M. Keck Telescope), and Australia (Anglo–American Telescope).	
Members Involved:	

Field Trip Name: W. M. Keck Telescope I

Start Date: 7 December 2003	***End Date:*** 9 December 2003
Continent:	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude: 19° 49.7'	***Longitude:*** 155° 28.7'
Name of site(cave, mine, e.g.): Keck Headquarters	***Keywords:***
Description of Work: Mid–infrared imaging of young stars to detect their dusty disks and spectroscopy to study their composition	
Members Involved:	

Field Trip Name: W. M. Keck Telescope I

Start Date: 5 May 2004	***End Date:*** 9 May 2004
Continent:	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude: 19° 49.7'	***Longitude:*** 155° 28.7'
Name of site(cave, mine, e.g.): Keck Headquarters	***Keywords:***

Description of Work: Mid–infrared imaging of young stars to detect their dusty disks and spectroscopy to study their composition

Members Involved:

Field Trip Name: Baade Telescope (Magellan I)

Start Date: 26 May 2003	***End Date:*** 31 May 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:*** La Serena
Latitude: –29° 0.2'	***Longitude:*** 70° 42.1'
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***

Description of Work: Molecular hydrogen imaging of young stellar outflows.

Members Involved:

Field Trip Name: IRAM 30 m

Start Date: Winter 2004	***End Date:*** Spring 2004
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***

Description of Work: Observations of formaldehyde around IRC+10216.

Members Involved:

Field Trip Name: Magellan 1

Start Date: 25 September 2003	***End Date:*** 26 September 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***

Description of Work: Spectral type determination of EXP4 and NGC 2660 candidates and stars in fields of view.

Members Involved:

Field Trip Name: Magellan I

Start Date: 27 July 2003	***End Date:*** 28 July 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Spectral type determination of EXP4 and NGC 6208 candidates and stars in fields of view.	
Members Involved:	

Field Trip Name: Swope 1 m telescope

Start Date: 5 March 2004	***End Date:*** 26 April 2004
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Open cluster survey (IC 2714 & NGC 5316).	
Members Involved:	

Field Trip Name: DuPont 2.5 m telescope, Las Campanas Observatory

Start Date: 11 May 2004	***End Date:*** 17 May 2004
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Spectral type determination of candidates and stars in field of IC 2714, NGC 5316, and NGC 6208.	
Members Involved:	

Cross Team Collaborations

Co−I Boss continues his collaboration with the NASA Ames scientists working on the Kepler mission.

Co−I Chambers is collaborating with Jonathan Lunine (University of Arizona NAI team).

As Chair of Astronomy Focus Group, Co−I Seager completed the "Astrobiology and the James Webb Space Telescope" recommendation to NASA. This effort involved participants both inside and outside of NAI. From NAI were Jonathan Lunine, co−chair (University of Arizona), Alan Boss (CIW), Tom Greene (NASA Ames), Joe Nuth (NASA Goddard), and Alycia Weinberger (CIW). Additional workshop participants from the NAI included Nader Haghighipour (CIW), Michael Mumma (NASA Goddard), and Maggie Turnbull (University of Arizona).

Seager also has ongoing collaborative work with Yuk Yung (JPL NAI team) and Drake Deming (NASA Goddard NAI team).

PI Solomon is collaborating with Bruce Jakosky (University of Colorado NAI team) on the history of Martian water.

Co−I Weinberger collaborated with Eric Becklin, Ben Zuckerman, and Andrea Ghez of the UCLA NAI team on observations of young circumstellar disks.